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EXPLANATION AND HISTORY OF THE NEW SOLAR CYCLE MODEL USED IN MARS PLANETARY PROTECTION ANALYSIS*

Mark A. Vincent[1]

In December 2000, it was decided to update the solar cycle/ Mars atmosphere model coded in the software used to do the orbit lifetime aspects of Planetary Protection (PP) analysis (Vincent, 2000). The old model was based on analysis done for the Mars Observer mission in the early to mid-1980's. Since then the atmospheric models of the scientific community have been refined. In particular, the empirical measurements obtained from the accelerometer on board the Mars Global Surveyor (MGS) mission during its aerobraking phase have been included. The new model used in the PP analysis is fitted to match the recent scientific results. This report is an expanded version of an earlier memo (Vincent 2001) written to justify the use of this model. The new model is shown to be valid while still retaining some conservatism.

Introduction

Planetary Protection

A previous paper (Vincent 1997) described a new method that was derived to remove some of the conservatism used in the analysis of orbital lifetime for satisfying the Planetary Protection (PP) requirements of the Mars Global Surveyor (MGS) mission. Subsequently the method was generalized (Vincent 2000) so it could be used for all Mars orbiters. However shortly afterwards it was discovered that the solar cycle/ atmospheric density model used in the orbit propagations included parameters that were also overly conservative. A new model was created, similar in form, but with significantly different parameters. This paper describes the new model and how it differs from the old one.

Solar Cycle Models

The art of solar cycle prediction can be considered at many levels. Measurements of the flux at the convenient wavelength of 10.7 cm (referred to as "F10.7") has been recorded for over 50 years and its good proxy, sunspot numbers, for an additional 200 years back

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in time. For planetary protection purposes the amplitudes of the dominant 11-year cycles in the emitted flux were considered to be independent. No other periodicities were modeled even though there are suggestions of a 22-year term (related to the way sunspots form) and longer periods such as 400 years.

Some of the more sophisticated models take a more of an extrapolation approach. They take into account the recent, especially the previous, cycle when making predictions of the next cycle. Although this method would seem particularly appropriate for the 20-year term of PP, this type of prediction was not included. Besides the complexity of implementing these models, extending this technique to more than a couple of cycles in the future has not been shown to be appropriate. Furthermore, the conservative manner with which the model values were chosen (discussed below) was tantamount to taking some of the recent solar activity into consideration.

The particular parameters to consider for the modeling are the best nominal high, median and low flux values for a cycle. Euler (1995) indicates that the proper values are 150, 110 and 70 (note units are Janskys equal to 10^{-26} watts per square meter per hertz, and will be subsequently dropped in this discussion). It is important to note that these values correspond to a distance of 1 AU away from the Sun.

Euler states he converted smooth Zurich sunspot numbers from 1749 through 1947 to smooth F10.7 values and combined them with actual F10.7 measurements up to his epoch. This represents over 22 cycles and creates the numbering scheme that he and this paper will use. As shown in the Figure (below, from Euler), Cycle 22 was of particular interest for the (short term requirements of the) Mars Observer mission, while Cycle 23 and beyond are of interest for current and planned Mars orbiters.

It is important to note that Euler states that the predicted continuation of Cycle 22 comes from a fit to only Cycles 9 through 21. However, the predictions for Cycle 23 come from all the complete known cycles, 1 through 21. Thus Cycle 23 prediction is the best representation of a nominal cycle. The values 150, 110 and 70 for the peak, median and trough of the 11-year cycle are evident on the figure. Also evident are the 2σ high and low values that represent the stochastic normally-distributed variation about the nominal cycle. Both the deterministic and stochastic variations play an important role in the modeling needed for PP analysis. In particular, the deterministic variations contribute heavily to the nominal lifetime of the satellite while the increase in density due to the stochastic terms significantly decreases the lifetime and provides the probabilistic framework of the analysis.

Nyquist (2001) obtained an independent result by looking at only the time period when there was solar flux data (Cycles 18 through 22) as opposed to including the Sun spot data. His analysis suggested a peak value closer to 175. This tends to supports the conservative value of 200 chosen by Bougher which is discussed below.

Atmospheric Density Models

While the modeling of the solar cycle has ample data but a scarcity of knowledge about solar dynamics, the modeling of the atmospheric density of Mars has a paucity of measurements but somewhat better understanding of the physics and chemistry involved. However up until recently only surface measurements and the molecular structure at approximate altitudes was known for Mars. The newest data comes from the accelerometer measurements taken while MGS was aerobraking. Although the sensitivity of the accelerometer is such that only the drag forces at near the periapse could be measured, knowing the density at these altitudes helps greatly in calibrating the models which can be extrapolated to the higher altitudes that the PP analysis is mainly concerned with. The present analysis relies on the sophisticated model of Bougher whose results are presented in the next section.

However, as described later, a simple model is actually employed in the orbit lifetime analysis. Its parameters are fitted to match the values from Bougher's model at appropriate points. The most fundamental assumption is that the logarithm (base 10) of the density for a given altitude is proportional to the solar flux value F10.7. The variation of density with altitude is given by a simple exponential model. Thus there are two sets of parameters to determine: those related to the proportionality between log density and those inherent in the exponential model. The latter includes solar flux and the reference density at the reference height and the scale height Note that the reference density is also a function of the nominal solar flux so the two modeling processes are intrinsically linked.

The solar flux incident of Mars was modeled to vary from two sources. One is the absolute flux emitted by the Sun that is described above. The other is the variation is the Mars-to-Sun distance as Mars moves about the Sun which creates an annual dependence for the received flux in an inverse R-squared manner.

History

Heritage of the Old Model

As could be predicted, there was some difficulty reconstructing the previous model that was done in the 1980's. Vincent, Sweetser and Barengoltz all did somewhat independent investigations of this history. A number of papers are relevant to the model development but the one by Yen (1985) is a good focal point. It translates the results of atmospheric modelers into graphs and tables which were directly used to create the algorithm used in the MARSMO subroutine that was implemented into the pertinent software (POLOP and POHOP) used in the Mars Observer mission design. Specifically Yen generated the F10.7 curves in her Figure 2 from Divine (1985) based on the model of Holland and Vaughan, (1984). Note that these curves are very similar to Euler's.

The density curves in Figure 3 of Yen's memo were generated by either her or Dwortzan at JPL using code provided under contract by Culp *et al* (1983). This Mars atmosphere model was an early version of the Stewart model that was delivered in 1987. This differs from the Culp *et al* version in that several parts of the model have been reformulated, and all of the parameter means, variations, and uncertainties have been re-evaluated. However, the Stewart model could not be too different because subsequent analysis at JPL used similar curves to Yen.

Comparison of Models

When comparing the old model to the new it is useful to consider the pertinent parameters:

<u>Reference Density</u>: Since this value is difficult to accurately model theoretically, it is understandable how the recent related empirical measurements have helped to a great degree. However, after a long series of assumed values, apparently with the proper comparisons, the numbers have not been changing a great deal. There are four "confusion factors" that have led to misunderstandings in the past. First, different Reference Heights (see below) have been used through the various missions. While conversions are straightforward if an exponential model is used, the choice of scale height is important.

The second area of potential confusion is the consideration of both a nominal solar cycle variation and a higher activity one. Yen included 2.87σ high curves in her memos since that was the relevant value to her probability analysis, however she clearly labeled them as the 99.8% percentile along with the nominal (50% percentile) curves. However the later work by Bass and Ceserone (1991) appear to present only the 2.87 σ curves. Since the reference density was an independent parameter that was input into POLOP and POHOP, the mismodeling could easily be compensated for, however there may have been other ramifications of using the 2.87 σ curves which are discussed below (see Amplitude of the 11-year Term).

The third factor that led to confusion is the difference between the global maximum of the density that is situated in the afternoon and near the equator. Most of the earlier work was referring to this value though originally it was thought to be at the sub-solar point. Some analysis was done to consider the average density around one satellite orbit, however that seemed to be more concerned with the ellipsoidal shape of the planet and the eccentricity of the orbit rather than any inherent global variations. As described below, recent modeling by Bougher has indicated that the proper orbital average is a factor of two less than the global maximum. This was further confused because according to Bougher *et al* (1999b) the MGS accelerometer indicated that the density was twice that of previously expected (Bougher 1996). Specifically, pre-MGS the global max was 1.2, orbital average 0.6 and after-MGS, global max was 2.4 and the orbital average was 1.2 (all in unites of 10^{-14} kg/m^3).

To complete the history of the reference densities, the sequence of values used by Vincent should also be explained. The first analysis was done with a highly conservative value Of 3.5 (again all in unites of 10^{-14} kg/m^3) from looking at Yen's graphs. Subsequently it was decided that this value was too conservative and the calculations were also done for a value of 1.75 (Vincent 1996). These two values (3.5 and 1.75) did seem to bound the problem at the time, though it should be remembered that the sources were quoting global max values but they were used as input to the software as orbital averages. In this time period Bougher (1996) produced his earlier number of 1.2. Of course, he meant this to be a global max and already knew that the orbital average would be much less, however it is perhaps fortuitous that this information was not communicated. In particular, Vincent (1996) took the 1.2 number, added some conservatism for uncertainty, and used 1.5 for the analysis used in the original MGS PP report. And since then, the halving by switching to orbital average has cancelled the doubling of Bougher's estimates. So the present situation of using orbital average of 1.5 is still valid.

The fourth confusion factor involves the relationship between the reference density and the method of fitting a sine wave to the 11-year variation. This is described below in the latter part of the 11-year cycle description. It is important to note that if there is any discrepancy in this area, it will negate some of the conclusions drawn in the next paragraph.

With the above caveat, the summary is that the global max value of 2.4 x 10^{-14} kg/m^3 appears to agree with the nominal curves of both of Yen's memos plus the most recent estimate by Bougher. Assuming that Bass did present the 2.87 σ high curves then with an appropriate scale height and stochastic adjustment, the reference density can also be made to match 2.4 x 10^{-14} kg/m^3. And the 1.5 x 10^{-14} kg/m^3 used for the orbital average since 1996 has also been consistent with this global average, albeit with some conservatism.

<u>Scale Height</u>: Although the models of Yen had scale heights as a function of height and solar activity, the exponential model in the software was restricted to a single value. This is true for both the old and new models. This is where an additional improvement in the software should be considered. In particular a relatively simple addition would be to have two values one each to be used above and below a value near 200 km where there is a known change in major constituent molecules. Note that for the orbiters to date this would not make a significant difference since the vast majority of the orbital lifetime is spent well above this boundary. However it may be significant for the Mars Reconnaissance Orbiter mission with its desired lower altitude.

<u>Amplitude of the 11-year Term</u>: This and the amplitude of the annual term are where the old and new models have major differences. Again looking at Yen (1984), Yen (1985), Bass and Cesarone (1991) and Bougher (2001), the first and last publications agree on a magnitude of the log density of +/- 0.35. The middle two and the MARSMO code have twice this, a magnitude of +/- 0.7. One explanation of how this happened is evident on the two sets of curves by Yen. In the 1984 graph, she has the density from a nominal flux curve with the +/- 0.35 but the (close to?) 3σ curve has a magnitude of +/- 0.7. Note the high frequency wiggles are due to the 27-day rotation of the Sun and are ignored

(smoothed out) in all other analyses. Both the nominal and 3σ curves of Yen's 1985 memo appear to have the larger amplitude 11-Year variation. Thus it is from here that the larger amplitude in MARSMO appears to have originated, perhaps because of choosing the worst case.

Another heuristic explanation that is not explicitly mentioned in the past memos involves the method of fitting the sine wave to the variation. It stems from the fact that the solar cycle is only roughly sinusoidal in shape, as can be seen in Euler's curves. In particular, it is rather flat near solar minimums. There are two different methods to fit the curve. The first ignores this flatness and fits a sine wave anyway, the max of the curve matching the solar max and the min of the curve close to the solar min. Obviously the median value is right in between these two extrema. The other choice recognizes the sinusoidal nature near the solar maxima and fits a curve with a median close to the solar min value. Obviously the amplitude of this curve is twice that of the previous method. The drawback to this approach is that the solar flux (and thus the density) are modeled to be low during the minimum "half" of the cycle. However, due to the logarithmic nature of the flux-density relationship this approximation is not too detrimental. Again, there is no real indication that the +/- 0.7 came from the latter method, though the former method to the extent possible was used when fitting Bougher's data. But there are two important points to be noted on this issue. One, the most important densities to achieve with one's model are those at solar maxima. With this in mind, the second point follows that the choices of reference density and 11-year amplitude are implicitly linked.

<u>Amplitude of the Annual Term</u>: It is the differences in this term which are least understood. The simple $1/R^2$ variation in solar flux gives a variation in the log density of +/- 0.2. Bougher gives values which are less than this and gives the explanation of global winds. However, Yen's and Bass's values consistently lead to the 0.56 value in MARSMO. One suggested reason (Tillman, 1998) is the fact that at perhelion, during the Southern Hemisphere summer, the South Pole dry ice cap sublimes to a greater degree than the equivalent event in the northern summer. However, this is usually thought of as a lower atmosphere phenomenon and surely was taken in to account in Bougher's model.

<u>Stochastic Term</u>: The old model used a coefficient of 0.3 to represent the increase in the log of the density was for a 1-sigma variation of the solar cycle about its nominal behavior. Looking at the old references, this seems like a reasonable value though Yen (1984) makes a big distinction between being at solar max or min. However, her 1985 curve can easily be used to determine a 0.88 difference for 2.87σ corresponding to a coefficient of 0.31. However, a re-examination of the more recent analysis (Bass and Cesarone 1990 and Bass 1990) suggested that the value might be a bit higher. In particular, in Table 10 of Bass the "One Sigma Error Factor" for the mapping orbit altitude for a longer period of consideration is 2.231. The log of this number, 0.348 is the coefficient of interest here. Thus 0.35 was chosen as the value for the new model. However, it may be worth re-addressing this issue since it has a substantial impact on the probabilistic aspect of the PP problem. Note that determining a value from a combination of Euler's (1995) and Bougher's (2001) analysis is somewhat complicated. Visual examination of Euler's figure (see Figure) indicates that the amplitude of a 1σ variation is

coincidentally about the same magnitude as the 11-year term. But as explained above, Bougher chooses a nominal high solar flux value higher than Euler so any concomitant stochastic variation in the former model would be smaller.

The New Model

Bougher's Results

Bougher (2001) has determined atmospheric densities using two models, namely the NCAR/UA Mars Thermospheric General Circulation Model (MTGCM) (Bougher *et al*, 1999a,b; 2000b) and the MSFC MARSGRAM-2000 (Justus *et al.*, 2000). Both incorporated the new data obtained from the MGS accelerometer during that mission's aerobraking phase. He looked at three solar flux values (70, 130 and 200 at the Earth's distance from the Sun) and three representative positions of Mars in its orbit about the Sun. His initial two tables refer to the density at the mid-afternoon point near the equator where the density is the greatest. However, he then looks at the opposite point on the orbit and discusses how since that value is about a factor of 20 less, the orbital average is about a factor 2 less than the maximum value.

The MARSGRAM values in his first table can be seen to be noticeably less than the MTGCM ones in his second table (both sets of results are presented in this memo in the Table at the end). Bougher states that this is due to the different method of modeling the outer atmosphere temperature response to solar flux, in particular the contribution of global circulation. He recommends choosing the average of the two models which results in the final value of 2.4×10^{-14} kg/m^3. Using Bougher's third table, it is apparent that the best value to use for the orbital average is half this, that is 1.2×10^{-14} kg/m^3. Note that to this precision, these averages can be derived in three ways. Namely, a straight average over all solar fluxes and orbital positions, doing a weighted average as he suggests (50% of the time the solar flux is near 130, 25% each at 200 and 70) or simply averaging the 130 flux, $L_s = 180$ values for the two models.

His tables were also used to determine the amplitude of the 11-year and annual variations in the density (see the Table). The amplitude of the annual term was determined by a simple $1/R^2$ consideration. It was then compared to the density dependence on the longitude of the Sun (L_s) also given in Bougher's tables. The determination of the 11-year amplitude is presented below, followed by the method to include the annual variation.

According to Euler's analysis, the three solar flux values that Bougher chose, namely 200, 130, 70 correspond closer to the maximum, nominal and minimum of a 1σ high excursion of the 11-year cycle rather than nominal. However, this is in agreement with his naming this a "moderate" cycle, if moderate is interpreted to mean moderately high as opposed to median. Thus, even though there is a good deal of conservatism involved, Bougher's peak values were accepted as conservative outer bounds of a nominal cycle. Note, that these choices of flux values also imply that the reference density of 1.2×10^{-14} is also higher than the true value. However there is self-consistency and although the important density at solar max is also high, it is not doubly so.

With the above assumptions the method for determining the amplitude coefficient for the 11-year cycle is as follows. As shown in Table 1, the log of each of the 18 (orbital max) density values (2 models x 3 flux values x 3 orbit positions) was calculated. This was done because for example, if the high peak of the density is $\rho_H = 10^H$ and the median is $\rho_M = 10^M$ then the positive amplitude of the sine wave used to represent the flux variation (see below) is $H - M = \log(\rho_H) - \log(\rho_M)$.

In this manner, six "high amplitudes" and six "low amplitudes" were calculated. Again, it is more important to fit and choose the high values for the reason that as the density increases exponentially, so does the drag and it effect on the orbit. However, contrary to the solar flux curves, the high amplitude of the density values is less in magnitude than the low amplitude. The asymmetry could be due to the mitigating effects at solar maximum due to global winds discussed in Bougher (2001). The average of the high amplitudes is about 0.35. Note that this is true with and without counting twice the medium value corresponding to the longitude of the Sun between periapse and apoapse (because it is near the average). Theoretically the larger low amplitude would suggest that the reference density could be lowered and the 11-year amplitude increased (similar to what was discussed above in the 11-year amplitude section). But if this was done it would have only created an amplitude of +/- 0.4, not the +/- 0.7 previously used. So the 0.35 amplitude was chosen, checking again the most important value, the modeled reference (orbital max) density time the solar max factor:

$$2.4 \times 10^{-14} * 10^{0.35} = 5.4 \times 10^{-14}$$

and seeing it is just a bit greater than the average (4.9) of the solar max values in Bougher's table (the offset due to averaging the log differences rather than the actual differences).

To explain the annual variation in the density, it is best to derive the full deterministic portion of the model from the initial assumptions:

$$\log(\rho/\rho_0) = A\,[F - F_0] = A\,[F_E\,(a_E/R_M)^2 - F_{E0}\,(a_E/a_M)^2]$$

where A is a scalar to be defined, F is the solar flux at Mars, F_0 its nominal value, F_E and F_{E0} are the corresponding values for the Earth, a_E and a_M are the semi major axes of the Earth and Mars and R_M is the radius vector of Mars's orbit. Note it can be thought of the Earth being in a circular orbit, though precisely the values of F_E have already, as standard practice, been adjusted to account for the eccentricity of the Earth's orbit. Thus

$$\log(\rho/\rho_0) = A\,(a_E/a_M)^2\,[F_E\,(a_M/R_M)^2 - F_{E0}\,]$$

Next the above described sinusoidal expression is substituted for the flux at the Earth and the expression for $a_M/R_M = 1 + e\sin(M)$ is used, where e and M are the eccentricity and Mean anomaly respectively, of Mars. It is valid to order e, the next term being $e^2\cos(2M)$.

$$\log(\rho/\rho_0) = A\,(a_E/a_M)^2\,[130 + 70\sin(2\pi(t-\tau_{11})/4014.1)*(1 + 2e\sin(2\pi(t-\tau_A)/686.98)) - 130]$$

Here $t-\tau_{11}$ and $t-\tau_A$ are the number of days from the 11-year (4014.1 days) and annual (686.98 days) epochs respectively (the values of τ_{11} and τ_A are explicitly given in the following section). Simplifying and substituting (a rounded up value) e = 0.1 gives:

$$\log(\rho/\rho_0) = A\,(a_E/a_M)^2\,[70*\sin(2\pi(t-\tau_{11})/4014.1) + 26*\sin(2\pi(t-\tau_A)/686.98) + 14*\sin(2\pi(t-\tau_{11})/4014.1)*\sin(2\pi(t-\tau_A)/686.98)]$$

The leading term $A\,(a_E/a_M)^2 *70$ is the 0.35 amplitude discussed above, so the appropriate values can be substituted for each coefficient yielding:

$$\log(\rho/\rho_0) = 0.35*\sin(2\pi(t-\tau_{11})/4014.1) + 0.13*\sin(2\pi(t-\tau_A)/686.98) + 0.07*\sin(2\pi(t-\tau_{11})/4014.1)*\sin(2\pi(t-\tau_A)/686.98)]$$

However, the old model was coded into the software with three separate sine terms apparently from a Fourier type fit to some of the density curves. The periods were close, but not exactly, the 11-year, annual and sum of the two frequencies. Note that if a fourth term representing the difference of the frequencies had also been included it could have been adjusted to be equivalent to the above expression. However, as indicated in the next section, instead the 11-year and annual terms only were retained with the amplitude of the latter equal to 0.2. This can be thought of as considering the annual term near when solar max is occurring and thus bounds the annual amplitude in a conservative manner. A future further improvement is recommended to include the cross-term indicated above (or equivalently a pair of sum and difference of frequency terms). Perhaps more precision in the eccentricity expansion could be added or ultimately the ephemeris value of R_M could be used.

The choice of 0.2 was compared to the results of looking at the log of Bougher's densities. This time the average was done over the different solar flux values and the difference between the value for $L_s = 270$ and $L_s = 180$ (corresponding to near periapse minus the mid point) and between $L_s = 180$ and $L_s = 90$ (corresponding to the mid point minus near apoapse) was considered. The results were not too consistent, the average of the MARGRAM high (periapse to mid) was less than 0.1 but the low amplitude was 0.2, for MTGCM the high was still but the low was 0.4. The asymmetry may be due to the fact that Mars's orbit is rotated quite a bit from the orientation of these longitudes but even so the scatter in the values was extreme. In particular, in only one case (MARSGRAM high) was the sequence of high at solar max, medium at solar nominal and low at solar min followed. However Bougher (2001) discusses in his report that the MTGCM model in particular models global winds that can cause the density to actually decrease slightly near solar max and perhelion.. In summary, the 0.2 annual term provides an adequate upper bound though there is plenty of opportunity to add more sophistication to the model if it deemed necessary.

Implementation of the Density Model

The atmospheric density at height h is modeled as:

$$\rho = \rho_0 * D * S * \exp[-(h - h_o)/H]$$

where the each of the parameters are explained in the following components of the model.

Exponential Altitude Model

The reference density ρ_0 is the density at the reference height h_o. It assumes that the term due to the deterministic variation (D) and stochastic term (S) are equal to unity, that is, they are at their nominal conditions. The scale height in the exponential model is H.

Deterministic (Time-varying) Model

The deterministic factor, D, is composed of the 11-year term and the annual term:

$$D = 10^{**}(0.35^*\sin(2\pi^*(JD-2450813)/4014.1) - 0.2^*\sin(2\pi^*(JD-2450992)/686.98))$$

where JD is the Julian Day. The left sinusoid is the 11-year (4014.1 days) term with amplitude 0.35. The right sinusoid is the Martian annual (686.98 days) term with amplitude 0.2.

Stochastic Model

The stochastic factor, S is simply:

$$S = 10^{**}(0.35^*z)$$

where z is the standard normally-distributed random variable representing the variation away from nominal.

Other Considerations and Future Work

Although the new solar cycle/density model has been shown to be an appropriate update to the PP analysis, there are several areas where modeling could be improved. With the exception of scale height modeling, it is known *a priori* that these changes would remove even more conservatism in the modeling and apply less restrictive PP requirements on missions. However, each one must be compared to the practical implications of implementing the changes and running the software that contains them. Briefly the proposed changes can be grouped as:

a) Reference Density: since this is an input to the software, no (JPL) modeling needs to be changed. However, as atmospheric scientists improve their models the updated values should be used. Also as the longitudinal and latitudinal dependence are better known, the assumptions about orbital averages could be re-examined. The best input would be an *in-situ* measurement such as determining the orbital decay of MGS in its mapping orbit.

b) Scale Height: Indications are that scale height are a function of height. Unless this can be modeled as a simple function, it is probably prudent to first consider a two value model. This comes from the generally accepted fact that the dominant molecular species changes near 200 km altitude. Thus one value of scale height could be used above and one value below. However, again it is worth noting that for the past and present orbiters, this change would not make a big difference in their orbital lifetime analysis since they reside well above this boundary for a large majority of their lifetime.

c) Periodic Variations: both the 11-year variation in the solar cycle and he annual term which is shown in the density could be modeled in a different manner than sinusoidal. However, unless a good functionality can be determined, it is probably better to keep the models as is. However the magnitudes as well as the

d) Stochastic Term: As mentioned above, the new coefficient of 0.35 might be overly conservative. Choosing a value somewhere between this and the old value of 0.30 might be more appropriate. This should be investigated further since it should have measurable effect on orbital lifetime probabilities and the resulting altitudes chosen to meet PP requirements.

e) Although this is only indirectly related to the solar cycle/density model, there are planned improvements to how the actual altitude is calculated when doing the density calculations in the fast orbiter POLOP. It propagates Mean Elements but a better calculation for drag would use the altitude determined by Osculating Elements. The capability of using an approximate method of conversion was not invoked as it was thought to be too inaccurate. Instead the altitude offset between using Mean and Osculating was known by comparison and applied to the final results. But again, the low and eccentric orbit for MRO suggests putting the appropriate conversion (which is available in separate software) into POLOP.

Conclusions

The amplitudes of the 11-year and annual term of the old model have been shown to be too conservative. The values of the new model seem to be much more appropriate, closer to the current scientific estimates. The new reference density was also shown to be appropriate, though in this case, a careful comparison of the string of values used indicates that the initial and final values do not differ greatly, rather there was a series of counter-acting factors. The amplitude of the stochastic term was increased in the new model and now bounds all suggested values. Overall, the new model will be of great benefit to Mars orbiter missions, by removing excessive conservatism in the older model while retaining some conservatism to account for the remaining uncertainties.

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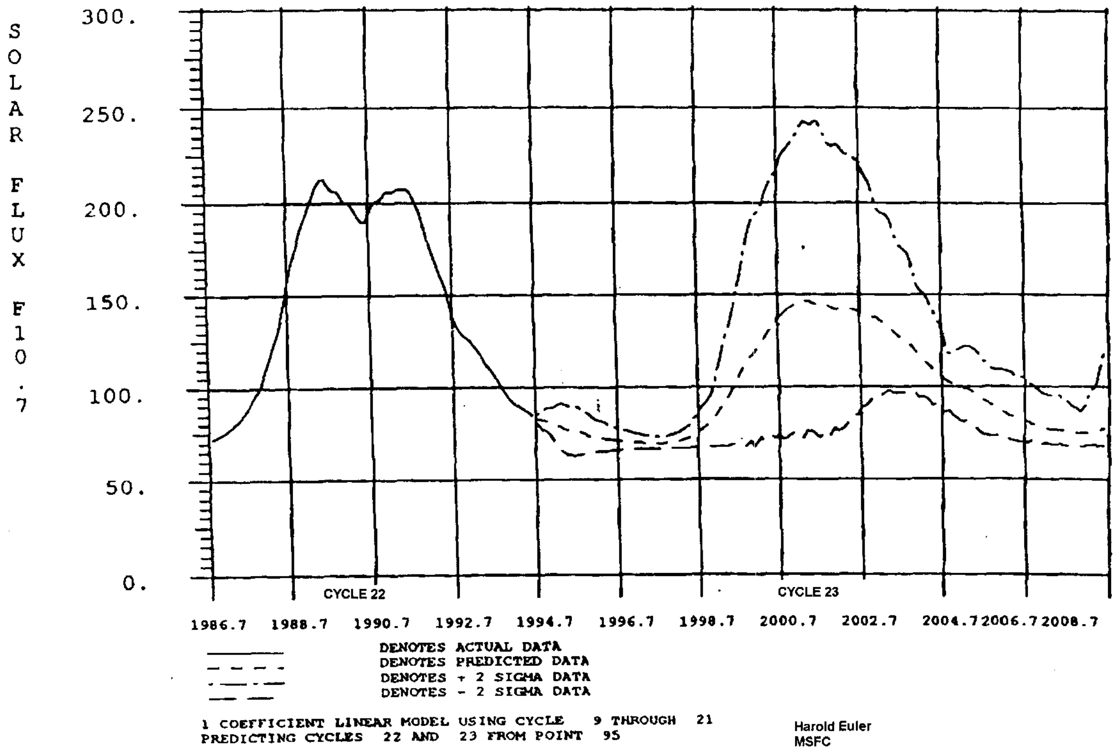
FIGURE 2 LONG RANGE ESTIMATES OF SOLAR ACTIVITY FOR CYCLE 22 AND 23



Solar Cycles 22 and 23

FIGURE
(from Euler, 1995)

TABLE

Mars Densities for a Variety of Solar Fluxes and Seasons

	F = 200	F = 130	F= 70	Log(200)	Log(130)	Log(70)	H= 200-130	L=130 - 70
MG Ls = 90	1.93	1.15	0.683	0.28556	0.060698	-0.16558	0.22486	0.22628
MG Ls = 180	3.26	1.81	0.976	0.51322	0.25768	-0.010550	0.25554	0.26823
MG Ls = 270	4.18	2.26	1.16	0.62118	0.35411	0.064458	0.26707	0.28965
MT Ls = 90	3.27	0.943	0.252	0.51455	-0.025488	-0.59860	0.54004	0.57311
MT Ls = 180	7.46	3.00	0.589	0.87274	0.47712	-0.22988	0.39562	0.70701
MT Ls = 270	8.70	2.97	0.900	0.93952	0.47276	-0.045758	0.46676	0.51851
Average							0.35280	0.42640
MG Ls = 180	3.26	1.81	0.976	0.51322	0.25768	-0.010550	0.25554	0.26823
MT Ls = 180	7.46	3.00	0.589	0.87274	0.47712	-0.22988	0.39562	0.70701
Average							0.35010	0.44480
					MG Only H	MG Only L	MT Only H	MT Only L
					0.22486	0.22628		
MG Ls = 90					0.25554	0.26823		
MG Ls = 180					0.26707	0.28965		
MG Ls = 270							0.54004	0.57311
MT Ls = 90							0.39562	0.70701
MT Ls = 180							0.46676	0.51851
MT Ls = 270								
Average					0.24920	0.26140		
MG Ls = 180					0.25554	0.26823		
MT Ls = 180							0.39562	0.70701
Average					0.25080	0.26310	0.44951	0.62641

Original data (Columns 2,3,4, Rows 2-6) from Bougher (2001). "H" is actually log(200 value) – log (130 value), "L" is log (130 value) – log (70) value. MG stands for MARSGRAM2000 and MT stands for MTGCM. Upper half of table represents the combined average of the two models while the lower half looks at the averages obtained by considering each model independently. L_s is Longitude of the Sun (representing where Mars is, in its orbit).